Earth-Science Reviews 185 (2018) 308–324

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Linkages of the dynamics of glaciers and lakes with the climate elements over the Tibetan Plateau

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ARTICLE INFO

Keywords:
Tibetan Plateau
Lakes and glaciers
Regional climate
Water resource

ABSTRACT

Future climate warming is expected to have a significant effect on the operation of Earth and Ecological systems. A key concern in the future is water resource availability. In regions such as the Tibet Plateau (TP) lakes and glaciers appear to be highly sensitive to climate forcing and variations in the size and extent of these system will have profound socio-economic and environmental consequences in South and Central Asia. Although the variety of glaciers and lake son the TP is a heavily researched and discussed topic the interaction between glaciers/lakes and climate change has not be thoroughly investigated. Here we present, through a review of existing studies and original remote sensing analysis, a reconstruction of changes in the spatial coverage of glaciers and lakes on the TP from 1990 to 2015 along with an analysis of climate data for the same period. The results revealed that these systems responded to changes in both temperature and precipitation but the nature of this response, and the controlling factor, was spatially diverse. During this interval the total number of lakes increased from 868 to 1207, thus a large number of new lakes (n = 339) formed. The total water surface area of the lakes increase from 38,823.3 km^2 in 1990 to 48,793.0 km^2 in 2015, at a rate of 383.5 $km^2\ yr^{-1}$. Over this period intensive glacial shrinkage occurred, primarily driven by increasing average temperature, except in the Karakoram Mountains where a slight increase in glacier extent was explained by low and stable temperatures along with increasing precipitation. The expansion of lakes in the central and northeastern TP can, therefore, be explained by a trend of increasing precipitation and the accelerated melting of glaciers associated with rising temperatures, both of which contributed to the enhanced total basin runoff. The shrinkage of lake areas along the Himalayan Mountains is accounted for by low precipitation coupled with high evaporation and limited basin space. The lakes within the Qaidam Basin express a complex pattern of response in association with fluctuating precipitation and strong evaporation. The pattern of shrinking glaciers and expanding lakes indicate that water-cycle processes on the TP have been accelerating during the past 25 years. Under current climates, and future climate change, the shrinkage of glaciers and the enlargement of lakes may be expected to continue to accelerate until a "tipping point" is reached when the meltwater of declining glaciers can no longer sustain the enhanced

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https://doi.org/10.1016/j.earscirev.2018.06.012
Received 17 June 2017; Received in revised form 13 June 2018; Accepted 14 June 2018
Available online 21 June 2018
0012-8252/

lake levels. Such a scenario would have severe socio-economic and ecological consequences for this region making the continued study of water-cycle activity across the TP an urgent priority.

1. Introduction

The Tibetan Plateau (TP), the highest and most extensive highland in the world with an extraordinarily sensitive ecosystem, is considered the amplifier of drastic global climate change (Ding et al., 2006; Song et al., 2014d; Sun et al., 2013a; Sun et al., 2013b; Sun et al., 2016; Zhang et al., 2013d). As the critical components in its ecological system, the dynamics of the lakes (Wu and Zhu, 2008; Zhu et al., 2010b) and glaciers (Kaab et al., 2012; Kang et al., 2009b; Molg et al., 2014) are of considerable significance with regard to regional responses to global climate change (Ding et al., 2006; Song et al., 2014b). The variations of hydrological circulation have remarkable impacts on soil conservation (Herman et al., 2015; Kong and Yu, 2013), vegetation productivity (Kramer et al., 2010; Zhang et al., 2013c), biodiversity (Jacobsen et al., 2012), livestock (Shang et al., 2014), land cover types (Molg et al., 2012), tourism (Wang et al., 2010), and socio–economic development (Sheng et al., 2005). Consequently, a number of studies have focused on the dynamics of lakes and glaciers on the TP (Tang et al., 2013).

Lakes play a pivotal role as regulators, sentinels and integrators of climate change (Li et al., 2014b; Yi et al., 2015). Regarding lakes along the Himalayan Mountains, the area of Yamzhog Yumco and Paiku Co sharply decreased in recent decades (Chu et al., 2012; Ye et al., 2007). The lake level of Yamzhog Yumco increased at a rate of 0.28 m yr^{-1} from 1996 to 2004, but then dropped rapidly at a rate of –0.5 m yr^{-1} in the period from 2004 to 2012 (Stofberg et al., 2017; Yang et al., 2008b; Zhang et al., 2015a). The total area of the Mapam Yumco Basin decreased by 34.16 km^2 from 1974 to 2013 (Ye et al., 2008a). Similarly, the shrinkage of lakes also occurred in the source region of Yellow River (Wan et al., 2014). Lakes were observed to expand, however, in certain regions. In the 2000s, Qinghai Lake began to expand (Liu and Liu, 2008; Shao et al., 2008; Li et al., 2012), with an elevation rate of 0.11 m yr^{-1} (2003–2009) (Zhang et al., 2011b). The increased rate of the Nam Co Basin was 1.27 km^2 yr^{-1} from 1970 to 2000 (Wu et al., 2007b). Between 1976 and 2010, the area of six closed lakes (Siling Co, Nam Co, Bam Co, Pung Co, Darab Co, and Zige Tangco) expanded by 20.2% in total area, accompanied by a 37.7 Gt increase in total storage (Lei et al., 2013). Additionally, lakes in both Nagqu and Kekexili have been continually expanding (Song et al., 2014b). In summary, lakes on the TP grew from 35,638.1 km^2 to 41,938.7 km^2 from the 1970s to 2011 (Song et al., 2013). The mass balance of lakes on the TP gained in the 2000s (Lei et al., 2013; Song et al., 2014a; Zhang et al., 2013a), regardless of the area or number of lakes (Wu et al., 2007a). Further, lakes' expansion accelerated from 2003 to 2009 (Zhang et al., 2011b; Zhang et al., 2011c), but the status of lakes on the TP is characterized by large water quantity and spatiotemporal variability.

Glacial melting is expected to impact the hydrologic cycle on regional and global scales (Yang et al., 2015). The glaciers on the TP act as a water storage tower and provide fresh water to almost 1 billion people in South and East Asia (Xu et al., 2009a). A large number of studies analyzed the spatial–temporal dynamics of glaciers on the TP (Aizen et al., 2007; Wang et al., 2011a), and a marked shrinkage of glaciers was revealed in recent decades (Bolch, 2007; Kong and Pang, 2012). Almost 17% of the Great Himalayan is covered by glaciers (Dyurgerov and Meier, 2004), but 50% of the glaciers in the Greater Himalaya of Zanskar (2001–2007), 84% of the glaciers in the western Himalaya (2001–2007), and 42% of the glaciers in the Karakoram (2001–2006) all exhibit a retreating trend (Bolch et al., 2012). In the west of TP, negative mass balance was found in the Dokriani glaciers (1992–2000) (Dobhal et al., 2008), and glaciers in the Mapam Yumco Basin decreased by 7.53 km^2 from 1974 to 2003 (Ye et al., 2008a). In central TP, glaciers retreated in the western Nyainqentanglha Range (Bolch et al., 2010b; Pu et al., 2006; Zhang et al., 2004), where 22% of the glacial mass disappeared from 1977 to 2010 (Shahtahmassebi et al., 2012). In the southeast of TP, the area of the Zhadang Glacier and the Gurenhekou Glacier have been continually reduced in the last decades (Yu et al., 2013), and the Halong Glacier experienced a significant shrinkage in length at a rate of –10 m yr^{-1} from 1981 to 2006 (Yao et al., 2012).

It is worth noting that numerous studies have explored the driving forces for the variations of lakes and glaciers under climate change (Wang et al., 2013b). The expansion of most lakes across the TP was caused by the accelerated melting of glaciers due to the rising temperature, as the number of glacial lakes increased in the Himalaya (Wang et al., 2011b), the central TP (Wang et al., 2013b), and the TP (Zhang et al., 2015b). Meanwhile, Zhu et al. (2010a) suggested that the increased temperature induced the melting of the glaciers, as well as the increased precipitation and the decreased evaporation, which caused a significant increase in the storage of Nam Co. The area of the Nam Co catchment increased by 37.45 km^2, while the glacial area decreased by 25.74 km^2 from 1970 to 2000 (Wu and Zhu, 2008). The decrease of lake evaporation contributed to about 4% of the increased water level in Nam Co (1998–2008) (Ma et al., 2016). Generally, many studies have provided abundant evidence for the dynamics of lakes and glaciers on the TP under climate fluctuations. Lei et al. (2014b) hold that the increased regional precipitation contributed to the significant expansion of closed lakes on the TP during 1990 to 2010, while others argue that the expansion of glacier–fed lakes was mainly caused by the increased temperature that accelerated the shrinkage of glaciers (Huang et al., 2011a; Yao and Yu, 2007; Ye et al., 2007). In addition to the melting glaciers, increasing precipitation and declining evaporation were also found to be crucial to the expansion of lakes in central Tibet (Bian et al., 2010; Zhu et al., 2010a).

Many studies have investigated the hydrology of lakes (Wu et al., 2014; Zhang et al., 2011a) but ignored the glaciers (Lei et al., 2013), or only focused on the lakes and glaciers within a small watershed (Gao et al., 2012a). Increasing temperature and precipitation, as well as the shrinkage of glaciers, could accelerate the water cycle (Cheng and Wu, 2007; Gong et al., 2006; Jin et al., 2009; Kang et al., 2010b), especially in recent decades. Because the climate–driven mechanisms of lake and glacier variations still remain unclear in different regions over the TP (Song et al., 2014b), more comprehensive studies are necessary to clarify the relationships among glaciers, lakes and climate. Therefore, this review seeks to answer the following questions: (1) What is the spatial distribution and variations of lakes and glaciers on the TP from 1990 to 2015? (2) What is the relationship between the dynamics of lakes and glaciers under global climate change scenarios?

2. Data sources and analytical methods

2.1. Glacier and lake database

In this study, a time series of satellite images were obtained from the Geospatial Data Cloud (http://www.giscloud.cn/) and the United States Geological Survey (www.usgs.gov/). A total of 903 Landsat scenes of Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and Operational Land Imager (OLI) were downloaded in the periods of 1990, 1995, 2000, 2005, 2010, 2013 and 2015 and most of the images had a cloud cover of less than 10%. The spatial distribution of images in 1990 and 2015 are exhibited in Appendix Fig. S1 A, B. The images, mainly from June to October in each research period, were selected

because summer precipitation is the main water source for lakes. Detailed image information appears in Appendix Table 1. Landsat images are characterized by the high spatial resolution and their objectivity, and they have been widely used for acquiring the status of glaciers and lakes globally (Bolch et al., 2010a; Wang et al., 2013b; Zhang et al., 2015b). Extracted images were utilized to monitor the status of the lakes in 1990, 1995, 2005, 2010, 2013, and 2015, and the glacial status in 1990 and 2015. Meanwhile, visual interpretation and manual vectorization were conducted by experienced remote sensing experts to re–correct the inaccurate water and glacier surface areas, which were checked using Google Earth images. Finally, the rivers and reservoirs were excluded by consulting lake experts, and a database of lakes and glaciers in the study area was established (Fig. 1).

2.2. Climate data

Regional climate dynamics are important driving factors for glacier and lake variability. The weather station data of temperature, precipitation, and evaporation were collected from the China Meteorological Administration (http://cdc.cma.gov.cn) and were processed to obtain the annual mean temperature (AMT), the annual mean precipitation (AMP), and the annual mean evaporation (AME). The spatial interpolation of temperature and precipitation were processed by Anusplin 4.2 (Centre for Resource and Environmental Studies, Australian National University, Canberra), and the Kriging interpolation method was used for the evaporation by ArcGIS 10.2 (ESRI, Inc., Redlands, CA, USA). The spatial changing rates of AMT, AMP, and AME were all calculated by Eq. 1 (Sun et al., 2013a):

$$\beta = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - (\sum X)^2} \tag{1}$$

where β is the changing rate of Y, n is the number of years, X is the number of time series (1, 2, 3,..., n), and Y is the annual average of climate factors in the corresponding year.

2.3. Rule for the partitions on the Tibetan Plateau

The characteristics of precipitation and the dynamics of glaciers on the TP are driven by atmospheric moisture flux: the westerlies (northern TP), Indian monsoon (southern TP), East Asian monsoon (southeastern TP), and the transitions in between (Yao et al., 2013; Yao et al., 2012). The westerlies, Indian monsoon and East Asian monsoon are critical to the climate patterns over the TP (An et al., 2012; Zhisheng et al., 2001). Hence, to systematically and comprehensively reveal the relationship among lakes–glaciers–climate on the TP in different districts, we divided the TP into eight regions (Fig. 8 I A–H) according to the gradient of the large–scale atmospheric circulation that is associated with the westerlies, Indian monsoon and East Asian monsoon.

3. Results and discussion

3.1. Dynamics of lake and glacier

3.1.1. Lakes

The lakes on the TP clearly expanded between 1990 and the 2015 in this study. The lake area shrunk remarkably between 1990 and 1995, then began to continuously expand from 1995 to 2010, and then slowly increased during 2010 to 2015. To better quantify the changes in different–sized lakes, we categorized the lakes into five classes: small (1–2 km^2), medium (2–10 km^2), big lake (10–50 km^2), large lake (50–1,000 km^2), and super lake (> 1,000 km^2), and detailed information for the number and area of lakes is given in Appendix Table 2. In 1990 and 2015, a total number of 868 and 1,207 lakes with a water surface area larger than 1 km^2 were detected on the TP, respectively. Small, medium, big, large, and super lakes in 1990 accounted for 26.0%, 36.1%, 21.5%, 15.9%, and 0.5%, respectively, compared to 29.7%, 35.7%, 20.2%, 13.8%, and 0.5% in 2015, respectively (Fig. 2B). The total number of lakes increased markedly by 41.6% from 1990 to 2015, and the biggest change occurred in small lakes with a large number (339) of new lakes formed. The total water surface area of the lakes increased from 38,823.3 km^2 in 1990 to 48,793 km^2 in 2015 with an

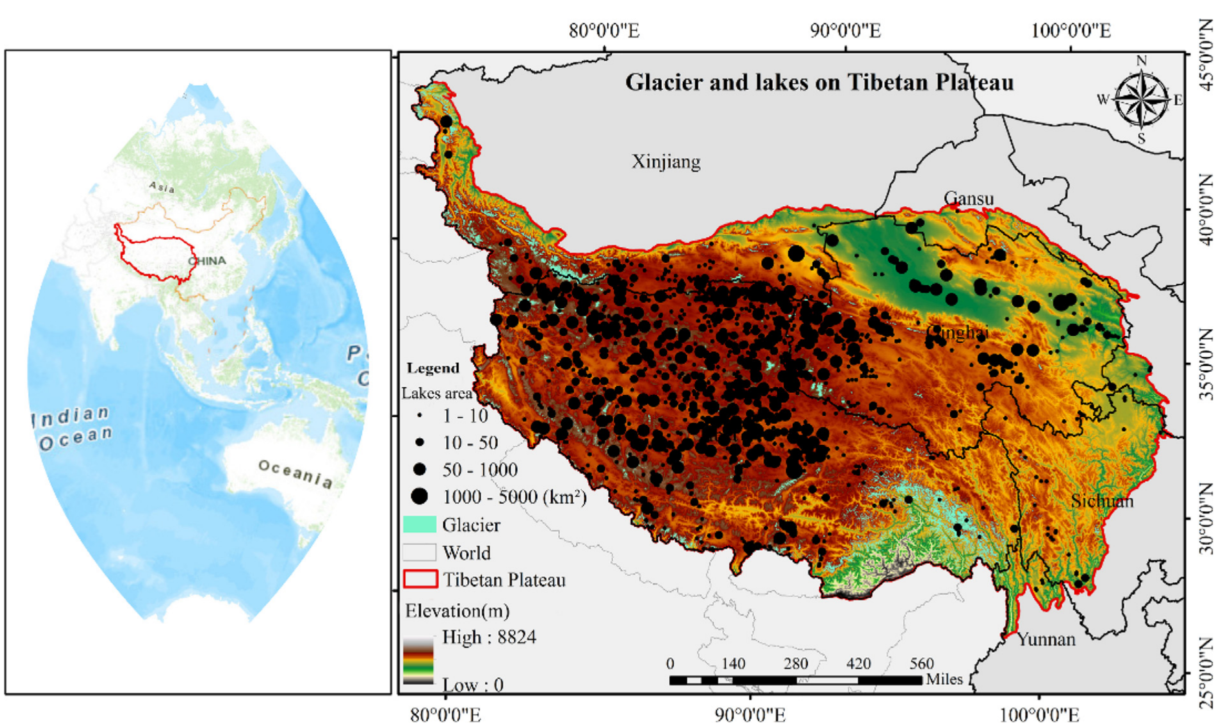

Fig. 1. The study area.

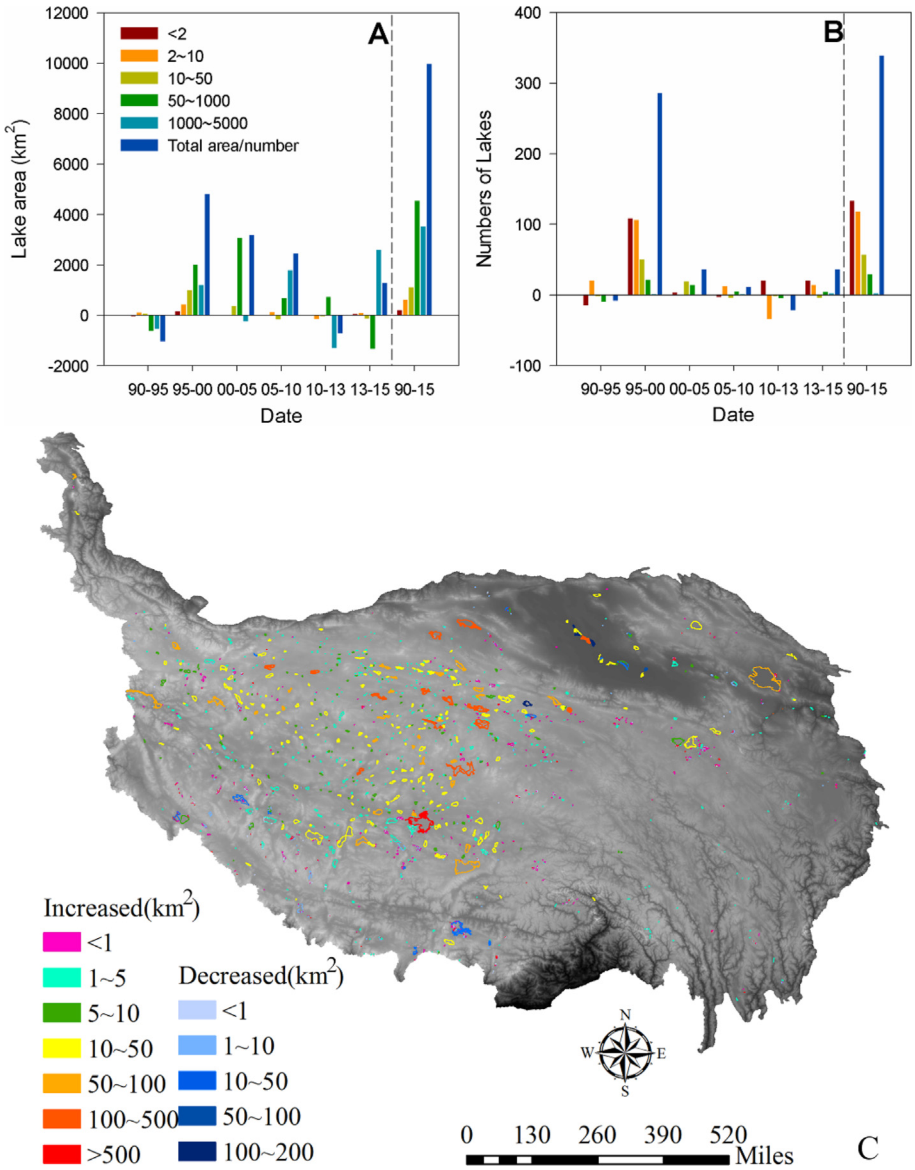

Fig. 2. Spatial–temporal distribution and variations of lakes on the Tibetan Plateau from 1990 to 2015. Graphs A and B represent the area and number of lakes, respectively; graph C represents the changed portion of lakes from 1990 to 2015; and the 90 represent the year of 1990, 95–1995, 00–2000, 05–2005, 10–2010, 13–2013, 15–2015 in graphs A and B.

increase rate of 20.4% (Fig. 2A). The small, medium, big, large, and super lakes increased by 197.6 km^2, 614.6 km^2, 1,102.3 km^2, 4,533.1 km^2, and 3,522.2 km^2, respectively, and the area of large lakes showed the largest increase compared to other sized lakes.

Spatially, Fig. 2C illustrates that the increased lakes are mainly distributed in the Qiangtang Plateau and around the Qinghai Lake. The lake with the greatest expansion was Siling Co, which increased by 647.5 km^2 (34.8%) from 1990 to 2015 (Appendix Fig. S2). A similar expansion trend of lakes was also found in Tibet (Kleinherenbrink et al., 2015), where a rapid enlargement was exhibited in Siling Co with a growth rate of 26.84 km^2 yr^{-1} (2003–2013) (Yi and Zhang, 2015). The water storage of Nam Co also increased by 3.27×10^9 m^3, with a total of 2.06 m rising in the lake level (2000–2009) (Zhang et al., 2013c) and a rate of 2.71 km^2 yr^{-1} enlargement in the lake area (1976–2009) (Zhang et al., 2011a). Similarly, the area of the lakes in the River Source Region increased by 6,866 ha from the early 1990 to 2004 (Huang et al., 2011b). Qinghai Lake also decreased in lake area between the 1970s and the early 2000s (Feng and Li, 2006; Shao et al., 2008; Shen and Kuang, 2003), while steadily increasing after 2005 (Liu et al., 2013a; Li et al., 2012). The lakes along the Himalayan Mountains and the Gangdisi Mountains, however, showed a stable unchanging tendency or even a decreasing trend, especially for the area of Yamzhog Yumco, whose lake area decreased by 31.50 km^2 from 1990 to 2015. Similar results for lakes were also noted in previous studies (Wan et al., 2014; Zhang et al., 2013a). The decreasing rates of 0.40 m yr^{-1}, 0.04 m yr^{-1}, and 0.03 m yr^{-1} were found in three lakes (Yamzhog Yumco, Peiku Co, Puma Yumco, respectively) in the southwest of the TP (2003–2009) (Zhang et al., 2011d). In addition, the area of lakes in the Hoh Xil region (Fang et al., 2016; Phan et al., 2012) and Qaidam Basin fluctuated in recent years.

The dynamic area data for 78 lakes on the TP was collected from 1990 to 2010 (Fang et al., 2016; Song et al., 2013; Yan and Zheng, 2015) to verify our conclusion. Similar to our results, most of the expanded lakes were distributed in the central TP, and the Har Lake, Qinghai Lake, Eling Lake, and Rige Co in Qinghai province also increased (Fig. 3E–H). The total area of the 53 lakes increased from 20,784.05 km^2 (1990) to 23,493.37 km^2 (2010) by 13.04%. The Siling Co expanded the most, with an increasing rate of 29.41 km^2 yr^{-1}

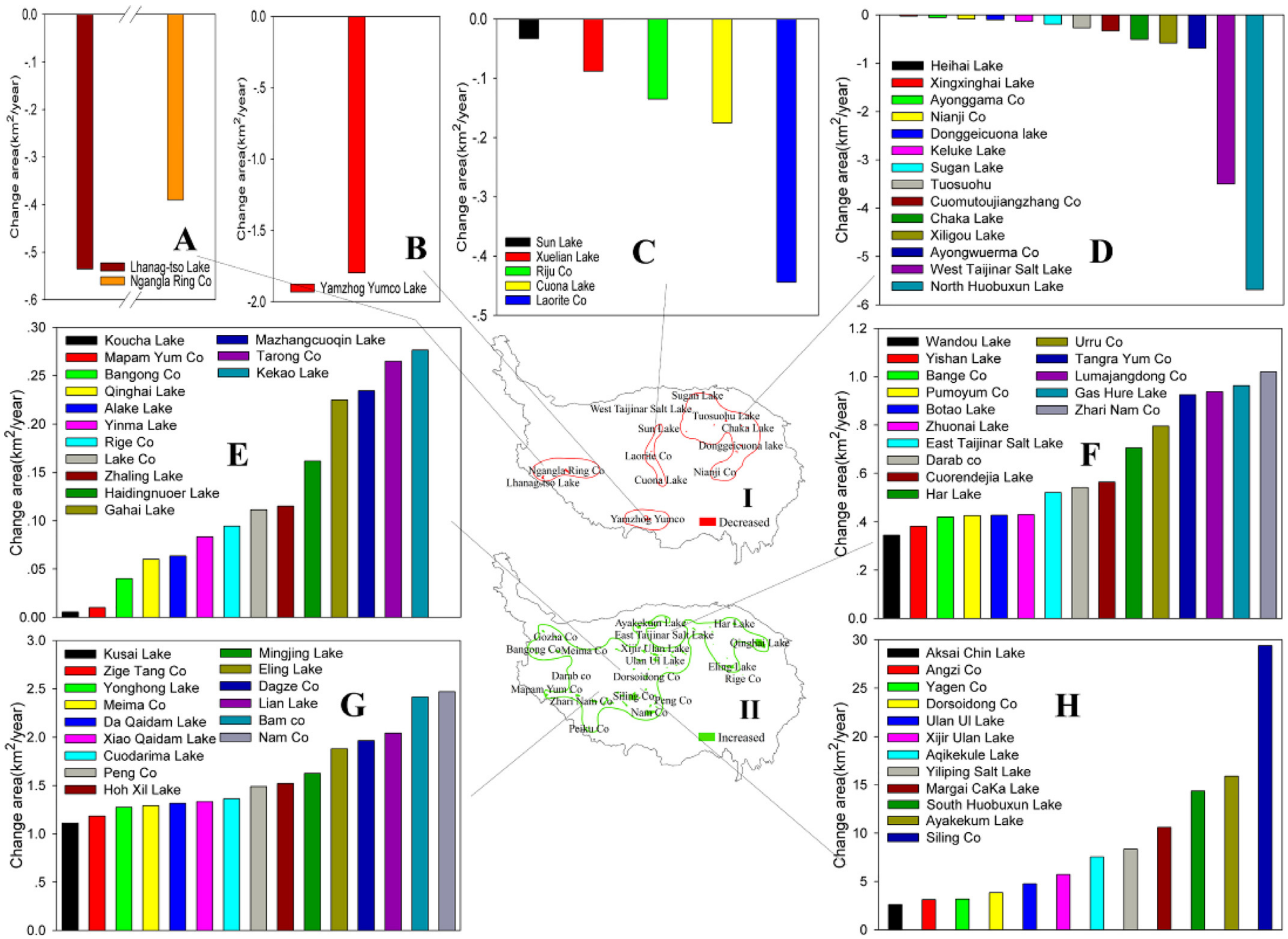

Fig. 3. Spatial distribution and variations of lakes ($km^2\ yr^{-1}$) from 1990 to 2010 on the Tibetan Plateau collected from previous studies. Graphs A, B, C and D represent the decreased lakes around the Mapam Yumco, the Yamzhog Yumco, the center and northeastern of the TP, respectively; graphs E–H represent the increased lakes mainly distributed in the center of the TP.

(Fig. 3H). Twenty–one lakes tended to decrease, however, including the lakes in the Himalayan Mountains (Fig. 3A, B, Yamzhog Yumco, Lhanag–tso Lake, and Ngangla Ring Co with decrease rates of $-1.80\ km^2\ yr^{-1}$, $-0.54\ km^2\ yr^{-1}$, and $-0.39\ km^2\ yr^{-1}$, respectively), the left of Bayan Har Mountains (Nianji Co at a rate of $-0.08\ km^2\ yr^{-1}$) (Fig. 3D), the Qaidam Basin (Fig. 3D), and a few lakes in the central TP (Sun Lake, Cuona Lake, and Laorite Co with corresponding rates of $-0.03\ km^2\ yr^{-1}$, $-0.18\ km^2\ yr^{-1}$, and $-0.44\ km^2\ yr^{-1}$) (Fig. 3C). In general, the water level of lakes on the TP have risen in recent decades (Liu et al., 2009a; Wang et al., 2013a; Yan and Zheng, 2015), as the area and number of lakes have expanded coherently and significantly (Lei et al., 2014b). The lakes on the TP are characterized by large quantity and spatiotemporal variability.

3.1.2. Glaciers

Glaciers on the TP have been experiencing a dramatic melting and shrinkage in the past 25 years. The status of glaciers is closely related to the real–time regional climate in the highlands; hence, we compared many images to acquire the minimum area of glaciers in each period. Meanwhile, to accurately reflect the dynamics of glaciers on the TP, we not only analyzed the spatial changes in the glacial region in this study but also collected the quantitative dynamics of glaciers from previous studies. Fig. 4 illustrates that glacial retreat was the dominant trend on the TP from 1990 to 2015. A large area and number of glaciers was retreating in the southeast (the Hengduan Mountains), the southwest (Gangdise Mountains and Himalaya Mountains), the center (the Nyainqentanglha Mountains and Tanggula Mountains), and the northeast (the Qilian Mountains) of the TP. The extremely sensitive glaciers are mainly distributed along the west Gangdise Mountains to the east Himalaya Mountains, and most of the glaciers have been shrinking continuously with a few small mountain glaciers disappearing completely in the Himalaya main ridge (Appendix Fig. S3). The glaciers in the Karakoram Mountains exhibited a slightly positive mass balance, however, and similar results were revealed in previous studies (Bolch and Stoffel, 2012; Kang et al., 2015; Yao et al., 2012). In general, most of the glaciers on the TP showed a negative mass balance (Kang et al., 2009a; Kehrwald et al., 2008; Pu et al., 2008; Ye et al., 2006), and an accelerating decreasing trend was observed in recent decades (Yao et al., 2012).

To better demonstrate our results, the dynamics of glaciers over the TP from previous studies were gathered (Appendix Table 3). The glaciers around the TP exhibited a drastic ablation trend in recent years (Fig. 5) (Li et al., 2008; Zhang et al., 2012c). The extremely sensitive glacial systems were mainly distributed in the edge–region of the TP (changes in area were approximately −10% to −20%, Fig. 5), and the relatively steady glacial systems were primarily found in the west Kunlun Mountains and around the Karakoram Mountains (changes in area were almost −5%, Fig. 5) (Wang et al., 2008b).

For the northwest of the TP, glaciers in the eastern Pamir decreased at an annual rate of $-0.24\%\ yr^{-1}$ (1963–2009) (Zhang et al., 2016). The

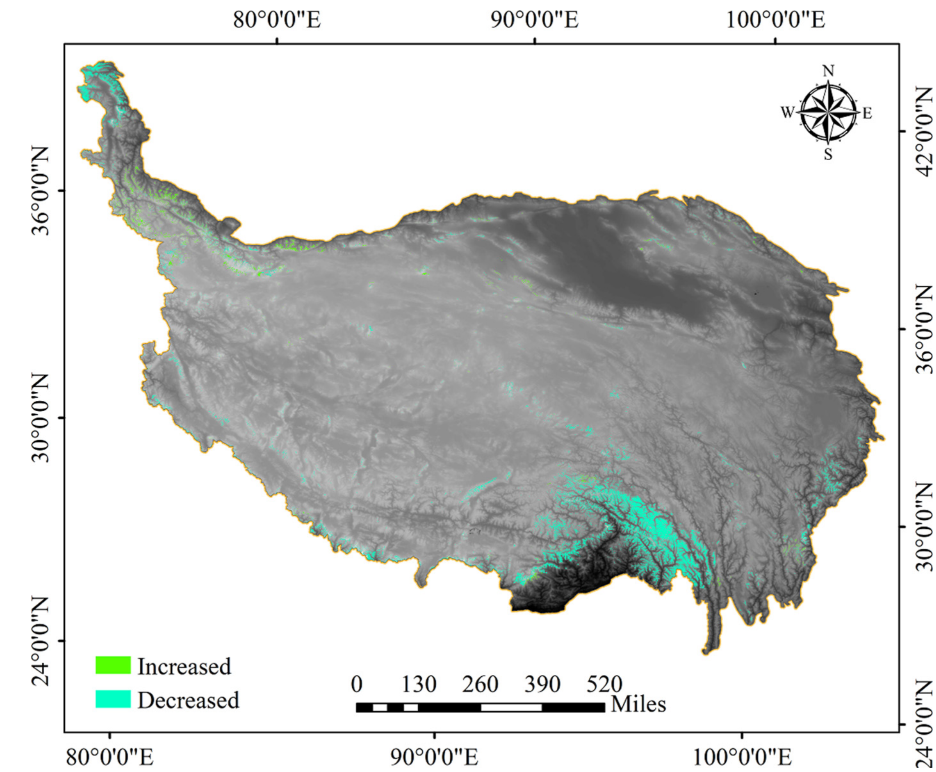

Fig. 4. Spatial distribution of the changed glaciers on the Tibetan Plateau between 1990 and 2015.

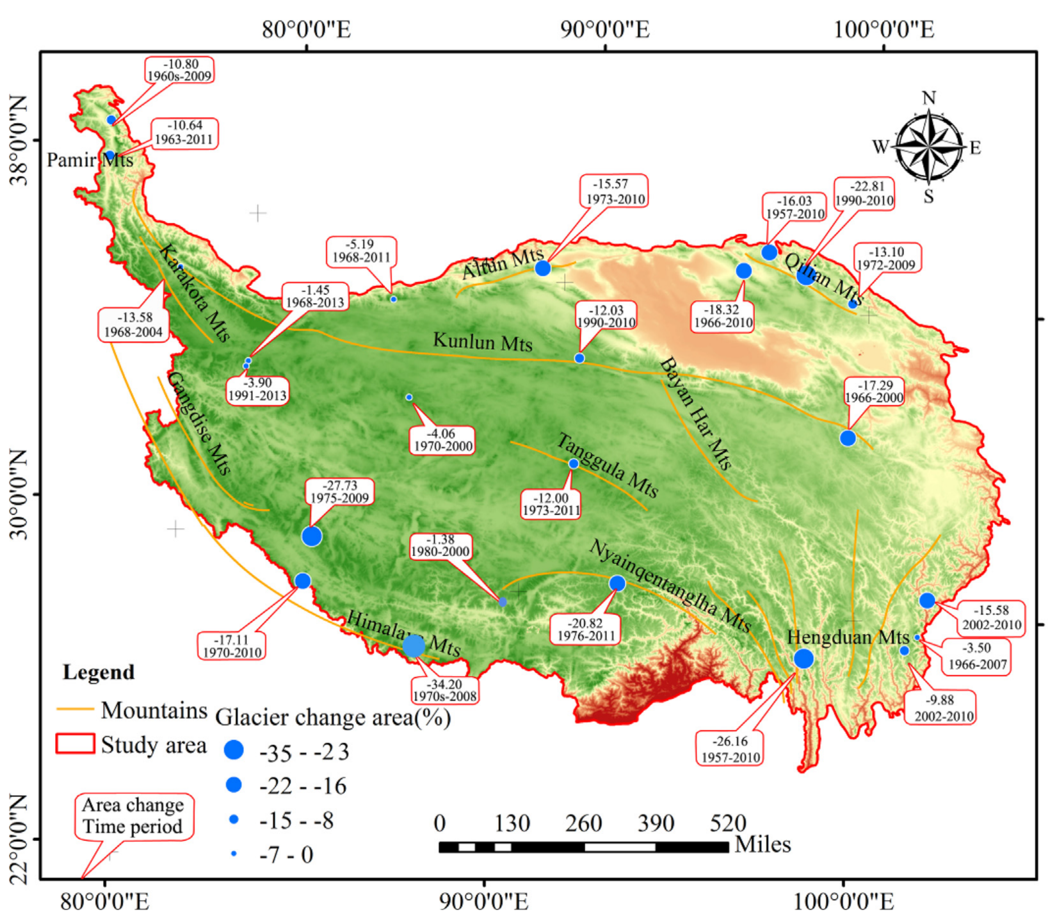

Fig. 5. Glacial dynamic on the TP (Appendix Table 3). The size of the blue dots denotes the magnitude of glacier area change, and the number with the dot shows the percentage of glacier area change and its time period.

loss ratio of glacial mass in the Muztag Ata and Konggur mountains was –11.2 m yr^{-1} (1990–1999) (Hou et al., 2011; Shangguan et al., 2006) and was –0.20 ± 0.01 m yr^{-1} (1968–1999) in the north bank of the Bangong Co Basin (Wei et al., 2015). The total glacial area decreased by 2.63 km^2 in the Xiongcaigangri region (1968–2013) (Li et al., 2015) and 16 km^2 (1991–2013) in the Depuchangdake region (Li et al., 2016).

In the west of the Himalaya Mountains, the Kangwure Glacier had a significant mass deficit, with a 34.2% glacial area loss since the 1970s (Ma et al., 2010). The changes in average thickness of the Kangwure glacier (2007–2010) and Naimona'Nyi glacier (northern branch, 2008–2013) were –2.70 m yr^{-1} and –1.11 m yr^{-1}, respectively (Tian et al., 2014). In the middle of the Himalaya Mountains, the glaciers in the Mt. Qomolangma region decreased by 1.44 km^2 (1992–2000), 1.14 km^2 (2000–2003), and 0.52 km^2 (2003–2008), respectively (Ye et al., 2009a). In the east of the Himalaya Mountains, the total glaciers in the Mapam Basin monotonically decreased, and the ablation rates of glaciers were –0.20 km^2 yr^{-1}(1973–1990), –0.32 km^2 yr^{-1} (1990–1999), and –0.36 km^2 yr^{-1} (1999–2003), with an accelerating ablation trend (Bruelheide et al., 2011; Ye et al., 2008b).

As for the center of the TP, glacial area in the Geladandong Mountain decreased 128.85 km^2 from 1973 to 2011 (Zhang et al., 2013b), the change in average thickness of Gurenhekou glacier was –3.82 m yr^{-1} between 2007 and 2011 (Tian et al., 2014), and the glacial runoff in the source region of Yangtze River contributed 11.0% of the total river runoff from 1961 to 2000 (Liu et al., 2009b). The glaciers in Nyainqêntanglha range (area > 5.0 km^2) shrank by 22.1% (1999–2013), with area change rates of –1.32% yr^{-1} (1975–1999) and –1.29% yr^{-1} (1999–2013) (Ji et al., 2016). The decreasing area of Zhadang Glacier and Gurenhekou Glacier were 0.64 km^2 and 0.23 km^2, respectively, from 1970 to 2007 (Yu et al., 2013).

In the southeast of the TP, the area of the Hailuogou Glacier decreased by 0.92 km^2 (1966–2007) (Liu et al., 2010a). The rates of shrinkage in the Hailuogou Glacier tongue and Baishui Glacier No. 1 were –6.16 m yr^{-1} (1990–1997) and –2.70 m yr^{-1} (1997–2004) water equivalent (Zongxing et al., 2010), respectively. The accumulated mass balance in the Hailuogou Glacier was –10.83 m water equivalent (1959–2003) (Yuanqing et al., 2008), with a retreating rate of –1.1 ± 0.4 m yr^{-1} from 1966 to 2009 (Zhang et al., 2010). Additionally, the 74 glaciers in Gongga Mountains shrank by 29.2 km^2 (1966–2009) (Pan et al., 2012).

The total glacial area in the eastern Qilian Mountains decreased by 1.20 km^2 (1972–2010) (Cao et al., 2014), and the area of the July 1st Glacier decreased by 5% (1956–2002) (Sakai et al., 2005). In the west of Qilian Mountains, the elevation level in Laohugou No. 12 glaciers increased by 18.6 ± 5.4 m (1957–2007) (Zhang et al., 2012b), and the area of Qiyi glacier declined from 3.08 km^2 to 0.58 km^2 (1990–2011) (Guo et al., 2015). Meanwhile, the ice volume for the Daxue Range (1957–2010) and the Danghenan Range (1966–2010) declined by 22.40% and 25.70%, respectively (Wang et al., 2016). In the east of the Qilian Mountain, the average glacial thickness in the Ningchan River Glacier No. 3 (1972–2009) and the Shuiguan River No. 4 Glacier (1972–2007) shrank by 9.4 m and 15 ± 8 m, respectively (Li et al., 2010; Liu et al., 2013b).

3.2. Climate trends

A significant ($P < 0.05$) increase of AMT was observed on the TP from 1990 to 2013, with a fluctuating upward trend from –1.05°C (1990) to 0.84°C (2013), and the average AMT was 0.49°C (Fig. 6A). In the period from 1990 to 2013, the AMT in the northwest and south of TP was relatively higher than in the northeast and the center of TP (Appendix Fig. S4 A). The temperature experienced a more rapid rise between 1990 and 1996 compared to other periods, while it decreased sharply from 1996 to 1997. Specifically, the average AMT was –0.47°C in 1990–1995, 1.06°C in 1996–2000, 0.42°C in 2001–2005, and 0.88°C in 2006–2013. Spatially, the relatively higher AMT appeared first in the southeast and northwest, then in the northeast and northwest, and the lowest value appeared in the middle region. Most areas of the TP experienced an increase in temperature, primarily distributed along the east of Himalaya Mountains and in the center and the east of the TP (Fig. 6D). Simultaneously, the decreasing temperature mainly manifested in the north and southeast of the TP, especially around the

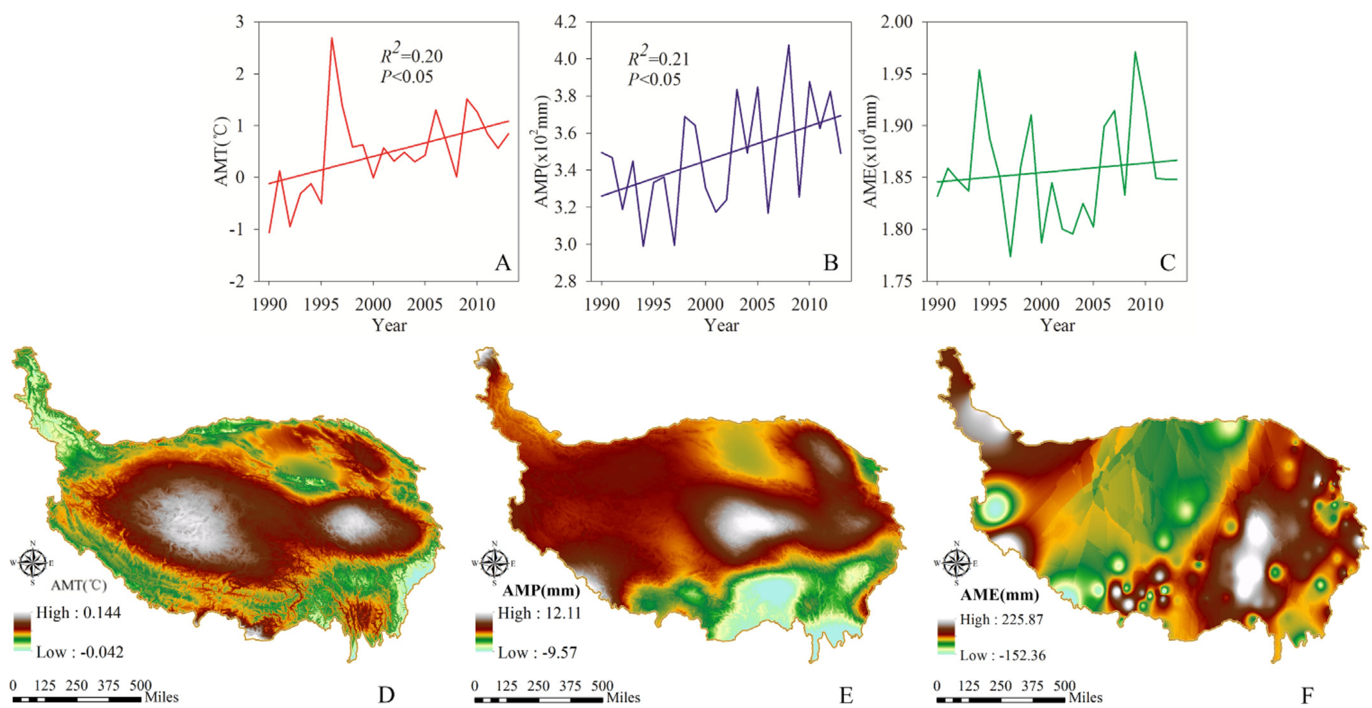

Fig. 6. Spatial patterns and variations of climate factors on the Tibetan Plateau from 1990 to 2013. Graphs A, B and C represent the dynamic of annual mean temperature (AMT), annual mean precipitation (AMP) and annual mean evaporation (AME), respectively; graphs D, E and F represent the spatial change rate of AMT, AMP and AME, respectively, on the TP.

Karakoram Mountains and the northwest of Sichuan Province (Fig. 6D).

During 1990 to 2013, a significant ($P < 0.05$) increase of AMP was observed on the TP, and the average AMP was 348 mm (Fig. 6B). The increasing trend of the AMP fluctuated with an average increase rate of 12.5 mm/decade^{-1} (1990–2013), and the averages of AMP were 332 mm in 1990–1995, 340 mm in 1996–2000, 352 mm in 2001–2005, and 362 mm in 2006–2013. Spatially, the average AMP presented a descending gradient from the southeast to the northwest (Appendix Fig. S4 B). Moreover, from 1990 to 2013, an increasing trend in precipitation was observed in most parts of the TP, especially in the central TP (Fig. 6E). The AMP remained relatively stable in the Qaidam Basin and declined in the south of TP, however, especially in the Hengduan Mountains and the east of Himalayan Mountains (Fig. 6E).

In general, the AME on the TP showed a fluctuating trend in the period from 1990 to 2013, with a slightly decreasing trend at a rate of 10.5 mm yr^{-1} (1990–2013). A similar phenomenon was found in previous studies, where the AME decreased at a rate of 13.1 mm decade^{-1} from 1961 to 2000 on the TP (Chen et al., 2006) and 12 mm yr^{-1} in the Namco basin (1998–2008) (Ma et al., 2016). The AME decreased from 1990 to 2003 and then increased from 2004 to 2013. It was observed that the AME from the east to the west of the TP gradually increased, and the west of TP accounted for a larger weight of total evaporation. In detail, higher AME was mainly distributed in the Ngari Prefecture, along the Himalayan Mountains and in the Qaidam Basin (Appendix Fig. S4 C). From 1990 to 2013, a decrease in evaporation was observed in the central TP from north to south, whereas an increasing tendency of AME was observed in the east Pamir Plateau, around the Mapam Yumco, Yamzhog Yumco and Cuorendejia Lake (Fig. 6F).

Overall, in recent decades, climate change on the TP has been characterized by rising temperatures (Wang et al., 2008a) that increased significantly in the eastern and central TP (Du and Ma, 2004; Xu et al., 2008; You et al., 2009). The AMT increased 1.89°C in this study period (1990–2013) on the TP, and the temperature rose 0.3°C per decade in most areas with an altitude above 4,000 m over the past three decades (Xu et al., 2009b). The precipitation was characterized by a rising trend in the central and eastern TP (Rangwala et al., 2009; Xu et al., 2008), but remained relatively stable in the Qaidam Basin and significantly decreased in the south. Meanwhile, no obvious variation was found in the evaporation on the TP during the study period. Slightly decreasing evaporation around the center of TP (Zhang et al., 2009; Zhang et al., 2007) or a relatively stable trend in the southwest (Liao et al., 2013) to the center–north of TP (Huang et al., 2011b) were revealed.

3.3. Dynamics of glaciers respond to the climate change in typical regions

To systematically understand the relationship between glaciers and climate fluctuations on the TP, eight typical regions (Fig. 7 I, A–H) were selected according to the gradient of the large–scale atmospheric circulation as well as their geographic features and dynamic representation of the glaciers. Data on the cumulative mass balance (CMB) of glaciers (Fig. 7 II, A–H) and the AMT (Fig. 7 III, A–H) in each region (Kang et al., 2015; Pan et al., 2012; Wang et al., 2015; Yao et al., 2012) were also collected. Simultaneously, the AMP (Fig. 7 IV A–H) was calculated by the extent of each region A–H in Fig. 7 I.

Significantly increased precipitation ($P = 0.050$, Fig. 7 IV A) and a relatively stable temperature trend (Fig. 7 III A) resulted in a slightly positive mass balance of the Muztag Ata Glacier in the Karakoram Mountains (Fig. 7 I region A), with a 298 mm yr^{-1} increase of CMB between 2006 and 2010 (Fig. 7 II A). More than 50% of the 42 glaciers showed a stable or slightly increasing trend with a mean rate of 8 ± 12 m yr^{-1} in the Karakoram ranges (2000–2008) (Scherler et al., 2011), and a total mass gain (0.37 ± 0.25 m yr^{-1}) in the glaciers was observed in the north of TP (Neckel et al., 2014). The results showed that the average AMT was –0.59°C from 1990 to 2013 in region A (Fig. 7 I), which was favorable for glaciers to remain stable, especially in the Karakoram Mountains with an obvious decrease of AMT (Fig. 6D). The increased precipitation due to the strengthening of westerlies (Lei et al., 2014a; Li and Wang, 2003; Zhao et al., 2012) presumably keeps the glaciers with a high albedo, which delays the melting of the glaciers (Lei et al., 2014a) in the Karakoram Mountains to a certain extent. More research is needed, however, to reveal why the glaciers in the Pamirs Plateau (decreased) and its surrounding glaciers in the Karakoram Mountains (slightly increased) presented different trends.

The Naimona'nyi Glacier (Fig. 7 I region B) exhibited a negative mass balance as a result of the increasing temperature, with an average CMB of –2,139 mm from 2005 to 2010 (Fig. 7 II B). A significant increase in temperature ($P < 0.0005$) and a slight increase in precipitation (Fig. 7 III B, Fig. 7 IV B) were found from 1990 to 2010. The high average AMT (0.92°C) from 2000 to 2008 may account for the rapid retreat (–60 m yr^{-1}) of glaciers in the western Himalayas (Scherler et al., 2011). In addition to the contributions from the increasing temperature, the strong average AME (Fig. S4 C) and low average AMP (134 mm) also had negative impacts on the glacial CMB.

Similar variations in CMB and climate variables were observed in region C (Kangwure Glacier, with an average CMB of –9,508 mm, 1992–2010, Fig. 7 II C) and region H (Qiyi Glacier, with an average CMB of –7,939 mm, 1989–2010, Fig. 7 II H) in Fig. 7 I. Both regions

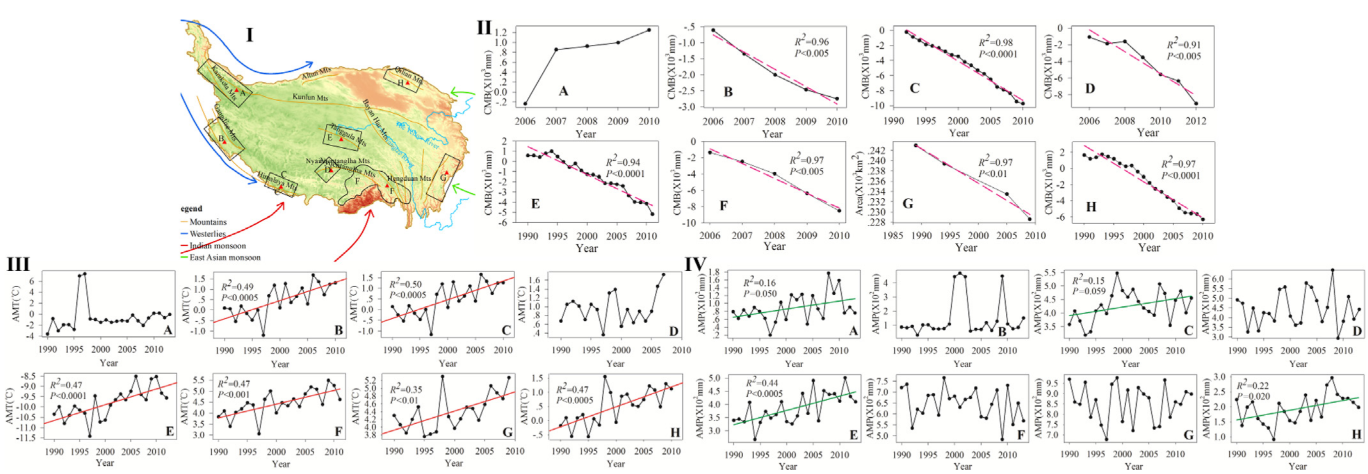

Fig. 7. Dynamics of a typical glacier and its climate characteristics in different regions on the TP. The red triangles in Fig. 7 I A–H represent the distribution of glaciers: A–the Muztag Ata Glacier, B–The Naimona'nyi Glacier, C–the Kangwure Glacier, D–the Zhang glaciers, E–the Xiaodongkemadi Glacier, F–the Parlung NO. 12 glacier, G–74 glacier in the Gongga Mountain and H–the Qiyi Glacier; and Fig. 7 II A–H, Fig. 7 III A–H and Fig. 7 IV A–H represent the cumulative mass balance (CMB), annual mean temperature (AMT) and annual mean precipitation (AMP) of glaciers in these regions, respectively.

showed a significantly increasing trend in temperature ($P < 0.0005$) (Fig. 7 III C, H). Recent studies have illustrated the clearly negative trend in the glacial CMB along the Himalayas (Bolch et al., 2012; Scherler et al., 2011). In detail, the mass balance of the Chhota Shigri Glacier was approximately –1 m in the period from 2003 to 2006 (Wagnon et al., 2007); the four glaciers on the Kangri Karpo Mountains retreated 15–19 m from 2006 to 2007 (Yang et al., 2008a); and in the Mt. Qomolangma Region, the glaciers retreated 0.12 $km^2\ yr^{-1}$ between 1992 and 2000, 0.22 $km^2\ yr^{-1}$ from 2000 to 2003, and 0.07 $km^2\ yr^{-1}$ during 2003 to 2008 (Ye et al., 2009b). The increase in temperature (Yao et al., 2012) and the high average AMT (0.47°C) gave rise to the glacial shrinkage in the central Himalayas. In addition, a slight decreasing trend of precipitation was exhibited in the Himalayas (1979–2010) (Yao et al., 2012) due to the weakening Indian monsoon (Thompson and Mountain, 2006; Yao et al., 2012), which has a negative effect on the glacial CMB. Additionally, the glaciers along the Himalayan Mountains have been melting at an accelerated rate in recent years (Berthier et al., 2007; Kehrwald et al., 2008b; Yao et al., 2012). As for region H, the total glacial area in the Su–lo Mountains decreased by 34.7 km^2 (1966–2000) due to the increasing temperature (Wang et al., 2008c). The negative mass balance of -0.77 ± 0.35 m yr^{-1} from 2003 to 2009 (Neckel et al., 2014) in the Qilian Mountains was dominated by the rapidly increasing temperature (Cao et al., 2014; Wang et al., 2016) and the high average AMT (0.49°C), especially the significantly increased summer mean temperature (Liu et al., 2013b). Thus, the increasing temperature (Fig. 6D) in the northeast reduced the albedo of glaciers, by inducing significant glacial melting (Wu and Zhu, 2008).

The results of this study demonstrated that the increasing temperature accounted for the intensive glacial shrinkage in the Nyainqêntanglha Mountains, and the change in CMB of the Zhang glaciers (Fig. 7 I region D, 2005–2012) was –1,132 mm yr^{-1} (Fig. 7 II D). The climate in this region was characterized by sharply increasing temperatures after 2004 and fluctuating precipitation from 1990 to 2010 (Fig. 7 III D, IV D). The increasing temperature melted the glaciers on the eastern Nyainqêntanglha (Ji et al., 2016), and approximately $13.93 \times 10^6\ m^3$ water volume was melting from the glaciers in Qugaqie basin (2006–2011), which accounted for 15% of the total basin runoff (Li et al., 2014a). The warming temperature (Fig. 6D) in the center of TP accelerated the retreat of the glaciers.

The change in mass balance for the Xiaodongkemadi Glacier (1989–2011, Fig. 7 II E) and the Da Dongkemadi Glacier (2000 –2012) (Wang et al., 2015) was –235 mm yr^{-1} and –242 mm yr^{-1}, respectively (Fig. 7 I region E). The mass balance in Xiaodongkemadi Glacier decreased by an average of 6.15 m (1969–2000) (Xing et al., 2010), with the average mass balance of approximately –136 mm yr^{-1} (1955–2008) (Gao et al., 2012a). Generally, the average level of the five glaciers in the Dongkemadi Glaciers increased from 5,421.6 m in 1996 to 5,593.4 m in 2006 (Huang et al., 2013), and thinned 7.34 m from 1955 to 2008 based on the model results (Gao et al., 2012a). A strongly significant ($P < 0.0001$) increase in temperature (Fig. 7 III E) with 0.3°C $10yr^{-1}$ in the Dongkemadi River Basin was the main driving force of the glacial ablation, and the glacial meltwater accounted for 66% of the increased runoff (1955–2008) (Gao et al., 2012a).

Many glaciers in region F showed dramatic shrinkage (Fig. 7 I). The average glacial reduction rate exceeded 80 m yr^{-1} in the Ata Glacier from 2005 to 2006 (Yao et al., 2012), and a rapid glacial retreat was found in Parlung No. 94 (–0.9 m yr^{-1}, 2005–2010) (Neckel et al., 2014), Parlung No. 10 glacier (–10.2 m yr^{-1}), and Parlung No. 390 glacier (–5.5 m yr^{-1}) from 2006 to 2008 (Song et al., 2015). The high value of AMT (4.44°C) and significantly ($P < 0.001$) increased temperature (0.359°C $decade^{-1}$) (Fig. 7 III F) resulted in the most negative mass balance of glaciers in the Parlung No. 12, with a CMB of –7,163 mm between 2005 and 2010 (Fig. 7 II F). This was consistent with the study of the Baishui Glacier No. 1 that illustrated the mean temperature of the active–layer increased by 0.24°C in 0.5–8.5 m depth of the glaciers during 1982 to 2009 (Wang et al., 2014). Additionally, the glacier area on the eastern Nyainqêntanglha Range decreased by almost 40.53% (1975–2013), which was mainly due to the rising temperature rate of 0.34°C $10yr^{-1}$ (Ji et al., 2016). Meanwhile, the distinctly decreased precipitation (Fig. 6E) probably accelerated the glacial shrinkage to a certain extent.

An obvious negative CMB was found in region G (Fig. 7 I). The Hailuogou Glacier retreated 0.47 m from 1990 to 1997 and 0.42 m from 1952 to 2009 (Li et al., 2013; Xie et al., 2010b; Zhang et al., 2012a). The continuously increasing temperature ($P < 0.01$, Fig. 7 III G) and the fluctuating decreasing precipitation (Fig. 7 IV G) have resulted in continuous shrinkage of the glaciers in the Gongga Mountain region (region G), where the glacial area decreased by 14.4 km^2 from 1989 to 2009 (Fig. 7 II G). The high AMT (4.39°C) and the significantly increasing temperature should be responsible for the shrinkage of the glaciers in Gongga Mountains, with an increasing rate of 0.27°C yr^{-1} from 1990 to 2009 (Zhang et al., 2012a). Similarly, rising temperatures, with a trend of 0.28°C $decade^{-1}$ (1988–2005) (Liu et al., 2010a), have had a significant effect on the increasing glacial retreat in the Hailuogou Glacier (Duan et al., 2013).

Overall, the increasing temperature was the dominant factor for the shrinkage of the glaciers on the TP (Liu and Chen, 2000; Qin et al., 2009; Yao et al., 2012), and the warming rate ranged from 0.16°C to 0.32°C per decade in winter. Approximately 41.2% of the glaciers were highly vulnerable from 1961 to 2007 due to their high sensitivity to climate change (Yang et al., 2015). The shrinkage of the glacial area in the Ertix River Basin, Junggar Basin, Yarkant River Basin, Dang River Basin, Shule River Basin, and Shiyang River Basin was 8%, 6%, 5%, 3%, 4%, and 20% (Kang et al., 2010a), respectively, in the period from 1960 to 2000. The loss of the glaciers was more serious than expected due to climate warming, especially in the Himalayan Mountains (Ma et al., 2010). The retreating rates of the glaciers were much larger after 1990 than in the 1980s due to the warming climate (Ye et al., 2007). The model results indicated that with temperature increase rates of 0.01, 0.03, and 0.05 K yr^{-1}, the glacial area of China would decrease 14%, 40%, and 60%, respectively, by the end of this century (Xie et al., 2006).

3.4. Hydrobalance mechanisms for typical lakes

First, eight regions of lakes were divided (Fig. 8 I, A–H) to systematically analyze the characteristics of the lakes and climate fluctuations on the TP, according to the gradient of the large–scale atmospheric circulation as well as their geographic features and dynamic characteristics. The dynamics of the lakes' area in the regions of A–H are demonstrated in Fig. 8 II. Accordingly, Fig. 8 III, Fig. 8 IV, and Fig. 8 V represent the variations of climate factors (AMT, AMP and AME) in the eight lake regions from 1990 to 2013, respectively, and the climate factors are calculated by the extent of each region A–H, as shown in Fig. 8 I. Then, to further reveal the relationship between the lakes and climate, we selected eight typical lakes for region A (Aksai Chin Lake), region B (Mapam Yumco), region C (Yamzhog Yumco), region D (Siling Co and Nam Co), region E (Man Co), region F (Cuorendejia Lake), region G (Qinghai Lake), and region H (Dongdabuxun hu) (Fig. 8 I). The basin perimeters and dynamic characteristics of the eight typical lake areas are shown in Appendix Fig. S5 A–I. To summarize, different hydrobalance mechanisms of lakes, which can result in different dynamic patterns, are shown in Fig. 9, and graphs A–H in Fig. 9 show the corresponding mechanisms of the lakes in Appendix Fig. S5 A–H.

The area of the lakes in region A (Fig. 8 I) showed an increasing trend at a rate of 7.8 $km^2\ yr^{-1}$ (Fig. 8 II A). The climate in this region was characterized by a slight increase in AMT (Fig. 8 III A), as well as a distinct increase in AMP ($P < 0.05$) (Fig. 8 IV A) and AME ($P = 0.056$) (Fig. 8 V A). From 1990 to 2013, the average of AMT, AMP and AME was –0.52°C, 104 mm and more than 2.15×10^4 mm, respectively. The increasing precipitation was closely related to the strengthening westerlies (Yao et al., 2012c), as the westerlies transported more water

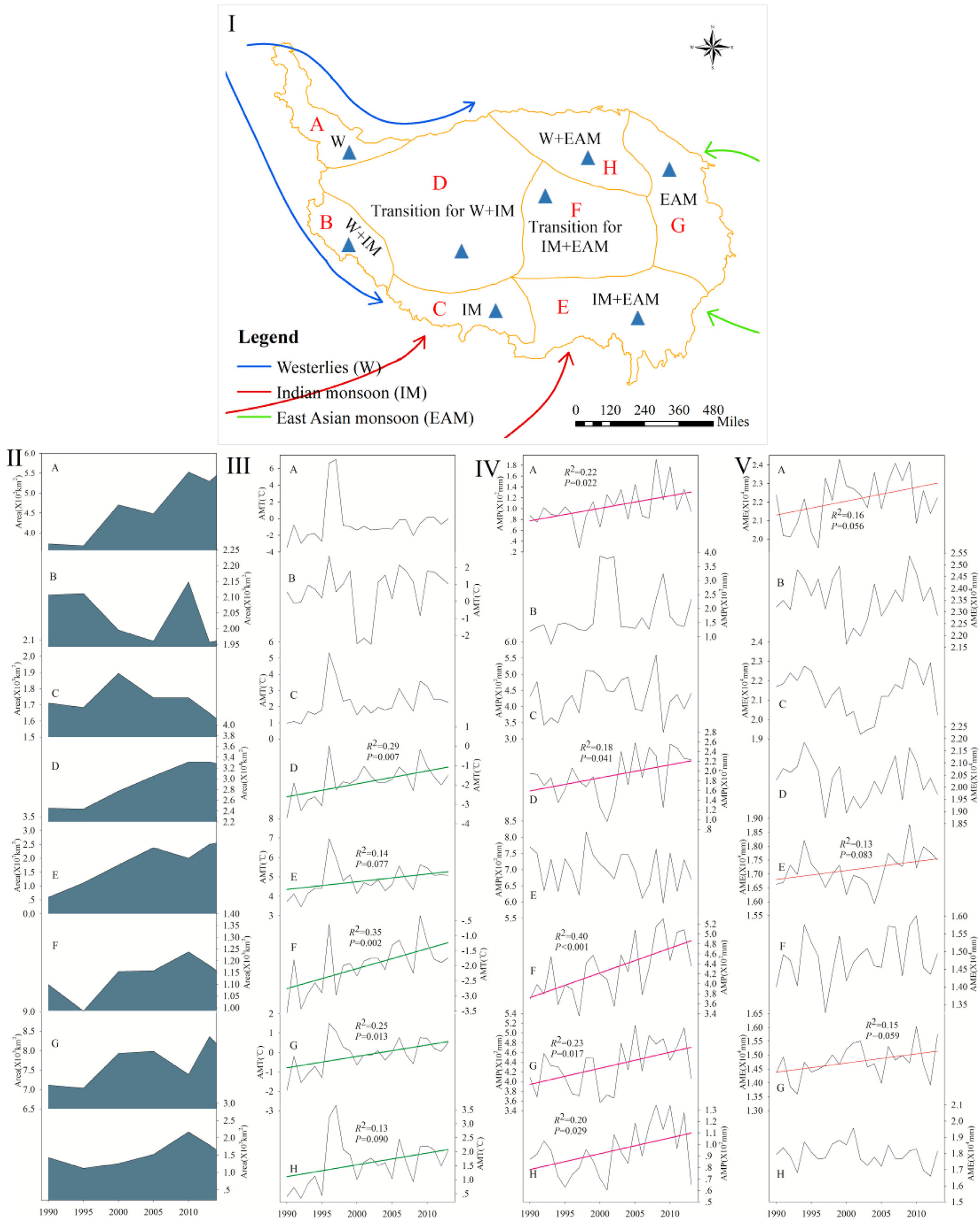

Fig. 8. The dynamic and climatic characteristics of the lakes in different regions on the TP. Fig. 8 I A–H represents the spatial distribution of lake regions that were driven by the atmospheric moisture flux: the westerlies (W), Indian monsoon (IM) and East Asian monsoon (EAM), and transition in between (Transition for W + IM, W + EAM, and IM + EAM); Fig. 8 II A–H represents the dynamic of lake area in regions A–H in Fig. 8 I; Fig. 8 III A–H, Fig. 8 IIV A–H, and Fig. 8 V A–H represent the variations of annual mean temperature (AMT), annual mean precipitation (AMP) and annual mean evaporation (AME) in regions A–H in Fig. 8 I, respectively.

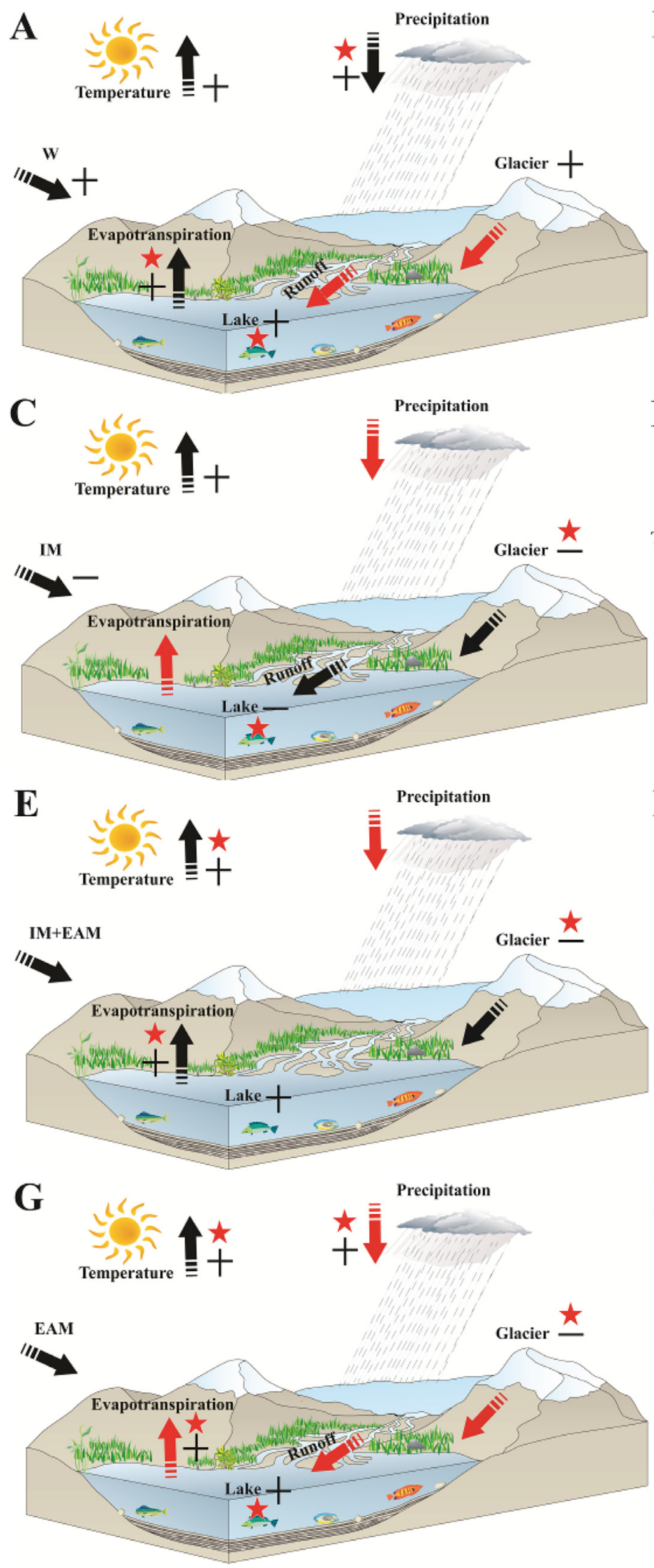

Fig. 9. Impact of climate variations in determining dynamic patterns of lakes under the atmospheric moisture flux: the westerlies (W), Indian monsoon (IM) and East Asian monsoon (EAM), and transition in between (Transition for W + IM and IM + EAM). The blue triangles in Fig. 8 I represent the precise location of the typical lakes: A–Aksai Chin Lake, B–Mapam Yumco, C–Yamzhog Yumco, D–Siling Co, E–Man Co, F–Cuorendejia Lake, G–Qinghai Lake and H–Dongdabuxun Hu. Graphs A–H in Fig. 9 represent the hydrobalance mechanism of the typical lakes of Aksai Chin Lake, Mapam Yumco, Yamzhog Yumco, Siling Co and Nam Co, Man Co, Cuorendejia Lake, Qinghai Lake and Dongdabuxun Hu, respectively. The red stars represent significant variation in factors and lake; the "+" and "–" represent the positive and negative variation of factors and lake; the black and red arrows represent the influence factors and the dominant factors for the variations of the lakes.

vapor to the northeast of the TP (Naidu et al., 2009; Yan and Zheng, 2015). In addition, the melting of the glaciers induced by the accelerating increased temperature around the basin (Scherler et al., 2011), together with the increasing precipitation (Fig. 7 IV A), generated a large runoff charging into the lakes. This could be the dominate water source for the expansion of Aksai Chin Lake downstream of the Karakoram Mountains (Fig. 9A).

Differently, a decreasing trend in lake area was found in regions B and C (Fig. 8 I), with decreasing rates of 5.87 $km^2\ yr^{-1}$ and 5.42 $km^2\ yr^{-1}$, respectively (Fig. 8 II B, C). In both B and C, the climate was characterized by a fluctuating AMT, AMP and AME (Fig. 8 III B, C, Fig. 8 IV B, C, Fig. 8 V B, C), with an average AMT, AMP and AME of 0.60°C and 2.26°C, 183 mm and 433 mm, 2.36×10^4 mm and 2.14×10^4 mm, respectively. In detail, the Mapam Yumco (in region B, Fig. 8 I) showed an obvious decreasing trend (Song et al., 2014c), with the lake area decreasing at a rate of 1.67 $km^2\ yr^{-1}$ (Appendix Fig. S5 I). Additionally, the area of Yamzhog Yumco (in region C, Fig. 8 I) also exhibited a decreasing trend in recent years (Song et al., 2014a; Wang et al., 2013a), with a declining rate of 1.21 $km^2\ yr^{-1}$ (Fig. S5 I). Similar shrinkage was investigated in Paiku Co from 1999 to 2010 (Lei et al., 2014b). In fact, a negative mass balance in lakes with areas larger than 10 km^2 (Shen et al., 2014; Song et al., 2013) and an increasing trend of lakes with areas larger than 1 km^2 (Wang et al., 2011b) along the Himalayas were revealed. The high evaporation, low precipitation (Li et al., 2014c), limited space of the basin (Fig. S5 B), and the warm air current of the Indian monsoon (Song et al., 2014c) were the main factors in the shrinkage of Mapam Yamco (Fig. 9B). Previous studies also found that the increasing temperature and decreasing precipitation accounted for the shrinkage of Lhanag–tso, which was next to the Mapam Yamco (Shen et al., 2014). Less precipitation resulted in smaller runoff rates for the Paiku Co and Mapam Yumco basins compared to Nam Co (Biskop et al., 2015). Additionally, low precipitation cannot offset the strong evaporation (Song et al., 2014a; Wang et al., 2013a) and the requirements of the hydroelectric power projects in the Yamzho Yumco (Ye et al., 2007) (Fig. 9C). In particular, the decreasing precipitation and the increasing evaporation led to the sharp reduction of the lakes in Yamzho Yumco after 2004 (Li et al., 2014c). Generally, the AMP of ~200 mm in lakes along the center of Himalayas to the West Gangdise Mountains made it difficult to offset the strong AME (Song et al., 2014c), which was caused by the warmer Indian monsoon. Previous studies have illustrated that the decreasing precipitation and the particular geographical and geomorphologic environment led to the shrinkage of the lakes in the south of TP (Song et al., 2013; Ye et al., 2007), which was in sharp contrast with the significant expansion of lakes on the central TP (Lei et al., 2013). In fact, the glacial meltwater also played an important role in the water balance (Biskop et al., 2016), and approximately 80% of the increase in runoff was caused by the melting of the snow and ice in the Mt. Qomolangma region. High summer temperatures resulted in the significant increase of the runoff in June (69%), July (35%), and August (14%) in Mt. Qomolangma region (1959–2005) (Liu et al., 2010b).

Generally, the expansion of the lakes in the center of TP was dominated by increasing precipitation, glacial meltwater and decreasing evaporation, which generated the enormous runoff charging into the lakes (Fig. 9D). A dramatic increase in area of the lakes was found in region D (Fig. 8 I), and the area of the lakes increased at a rate of 329.29 $km^2\ yr^{-1}$ during 1990 to 2015 (Fig. 8 II D). A significant increase in temperature ($P < 0.01$) (Fig. 8 III D) and precipitation ($P < 0.05$) (Fig. 8 IV D) was observed in region D, with the rates of 0.92°C $decade^{-1}$ and 11.73 mm $decade^{-1}$ from 1990 to 2013, respectively; and the evaporation exhibited a slightly decreasing trend at a rate of 23.5 mm yr^{-1} (1990–2013) (Fig. 8 V D). Similarly, in the center of TP, an increase in precipitation was observed (Liu et al., 2009a) and modeled (Yang et al., 2011). Coherent growth of the lakes in Siling Co and Nam Co was observed during different periods (Liao et al., 2013), with the increasing rates of 26.64 $km^2\ yr^{-1}$ and 2.93 $km^2\ yr^{-1}$ from 1990 to 2015, respectively (Appendix Fig. S5 I). The AMT in Nam Co increased at a rate of 0.40°C $decade^{-1}$ in the period from 1976 to 2009 (Zhang et al., 2011a). Additionally, in the Siling Co basin, the precipitation increased at a rate of 17.70 mm $decade^{-1}$, and the evaporation decreased at a rate of 33.35 mm $decade^{-1}$ in the hot seasons (1966–2013) (Yi and Zhang, 2015). Quantifying analyses showed that the lake inflows, precipitation, and evaporation contributed 49.5%, 22.1%, and –18.3%, respectively, to the total water storage change from 2003 to 2012 in Siling Co (Zhou et al., 2015). Rainfall–runoff, glacial melting, precipitation, lake percolation, and evaporation accounted for 104.7%, 56.6%, 41.7%, –22.2%, and –80.9%, respectively, of the increased lake level of Nam Co (1980–2010) (Wu et al., 2014). The glacial meltwater that was recharged into the runoff was an important water source (Gao et al., 2012a; Shi et al., 2016; Song et al., 2014d), since the glacial runoff accounted for 60% of the total runoff in the Da Dongkemadi Basin (1955–2008) (Gao et al., 2012a). The ice volume for the Siling Co catchment was approximately 36.37 km^3 (Bian et al., 2010), whereas the glacial area decreased by 34.76 km^2 from 1990 to 2011 (Du et al., 2014). Therefore, the rising temperature (0.56°C $decade^{-1}$ in Siling Co during summer, 2000–2013) (Yi and Zhang, 2015), as well as the humid climate, resulted in massive glacial melting (Yi et al., 2015) and generated the extensive runoff (Gao et al., 2012b) in spring, autumn, and winter in central Tibet (Liu et al., 2009a). The model results also demonstrate that the glacial mass loss accounted for 11.7% (in Siling Co), 28.7% (in Nam Co), and 11.4% (in Pung Co) of the total rising in lake level between 1999 and 2010 (Lei et al., 2013; Lei et al., 2013).

A steady increase in water area was revealed in region E (Fig. 8 I), with an increase rate of 8.37 $km^2\ yr^{-1}$ (Fig. 8 II E). The climate in this region was characterized by increasing temperatures ($P = 0.077$) (Fig. 8 III E) with a rate of 0.56°C $decade^{-1}$, stable precipitation ranging from 596 mm to 816 mm, and slightly enhanced evaporation (Fig. 8 IV E, Fig. 8 V E). Through the stable precipitation and the slightly increased evaporation, the precipitation with an average of ~700 mm and the glacial melting led to a 2.3 km^2 expansion of Man Co (Fig. 9E). Man Co is located in the southeast of TP with all sides coupled by glacial mountains. Even if the persistent increase in temperature accelerated the glacial melting, however, the geographical and geomorphologic environment (Fig. S5 E) limited the continuous expansion of Man Co. Thus, the area of the lakes was also shaped by their tectonics (Yan and Zheng, 2015).

There was an abrupt increase in the area of the lakes in region F (Fig. 8 I), with a rate of 1.61 $km^2\ yr^{-1}$ (Fig. 8 II F). A significant increase in temperature ($P < 0.005$, 0.059°C yr^{-1}) and precipitation ($P < 0.001$, 2.77 mm yr^{-1}) (Fig. 8 III F, IV F) and a slight increase in evaporation were observed in this region (Fig. 8 V F). A significant increase in precipitation led to the expansion of most lakes in region F. As a non–glacier–fed lake, the Cuorendejia Lake showed a slight enhancement in evaporation and an increase in temperature, which would be the main reasons for the 20.4 km^2 decrease of this lake from 1990 to 2015 (Fig. 9F). Meanwhile, the lack of glacial meltwater supply could be an important reason for the shrinkage of Cuorendejia Lake, since the glacial meltwater acts as a major water source for the lakes on the TP (Gao et al., 2012a; Song et al., 2014d). For example, Siling Co expanded dramatically, while Lake Co (next to Siling Co) remained stable. As a result, the lack of glacial meltwater in Lake Co rendered the two lakes very different, in spite of their similar climate features (Song et al., 2013). The marked variations between Cuorendejia Lake (decreased) and its surrounding lakes (increased), however, suggested that additional mechanisms may be involved in region F (Fig. 9).

The area of lakes in region G (Fig. 8 I) clearly increased at a rate of 37.09 $km^2\ yr^{-1}$ (Fig. 8 II G). A significant increase in temperature ($P < 0.05$) (Fig. 8 III G), precipitation ($P < 0.05$) (Fig. 8 IV G), and evaporation ($P = 0.059$) (Fig. 8 V G) was found in region G, with annual average values of –0.11°C, 432 mm, and 1.48×10^4 mm from 1990 to 2013, respectively. Qinghai Lake is located in the temperate semi–arid

climate zone, which is mainly supplied by precipitation and runoff. The area of Qinghai Lake increased at a rate of 24.32 km^2 yr^{-1} from 1990 to 2015. The significant increasing precipitation (Zhang et al., 2011c) and rapidly melting glaciers (Cao et al., 2014; Wang et al., 2016) gave rise to the expansion of Qinghai Lake. More than 70 of the inflowing rivers that were distributed around Qinghai Lake, together with the enhanced runoff caused by the increasing precipitation, were the primary supply sources for Qinghai Lake (Yan and Zheng, 2015). Meanwhile, the increasing temperature and precipitation made the climate in Qinghai Lake become much warmer and wetter (Liu et al., 2014), which accelerated the melting of the glaciers (with a melting rate of 300 mm per year in Qiyi) around the lake, and the glacial water became an important source for the expansion of Qinghai Lake (Song et al., 2013; Zhang et al., 2011c). The evaporation of the lake was much larger than the precipitation (Cui and Li, 2015; Haginoya et al., 2009; Song et al., 2014d), however, where the annual evaporation of the lake offset 23.42% of the precipitation in the basin (Cui and Li, 2015) and weakened the expansion of Qinghai Lake. Additionally, human activities have also had negative impact on the expansion of Qinghai Lake (Yan and Zheng, 2015).

The area of the lakes in region H (Fig. 8 I) increased slightly at a rate of 3.08 km^2 yr^{-1} (Fig. 8 II H). The AMT and AMP both significantly increased (Fig. 8 III H, IV H), with average increase rates of 1.60°C yr^{-1} and 94 mm yr^{-1}, respectively. The evaporation in this region exhibited a stable trend (Fig. 8 V H), with a strong average evaporation exceeding 1.79×10^4 mm yr^{-1} that was much higher than the precipitation (Xie et al., 2010a; Li et al., 2007). Although a significant increasing trend was observed in precipitation, the climate of this temperate arid climate zone was primarily controlled by evaporation and the accelerating increased temperature (Xie et al., 2010a; Li et al., 2007; Xu et al., 2006). Relatively low precipitation and high evaporation resulted in the uncertain variations of Dongdabuxun Lake (Fig. 9H). Lakes in the Qaidam Basin experienced intense fluctuations from 1990 to 2015, with many lakes newly forming or disappearing throughout the different periods. The obvious expansion of the lakes occurred under relatively abundant precipitation, while dramatic shrinkage appeared in dry seasons. Moreover, the shrinkage of the salt lakes in the Qaidam basin was probably caused by human exploitation (Wan et al., 2014) to acquire the resources of gypsum, mirabilite, and trona (Yan and Zheng, 2015).

In summary, both the increasing precipitation and accelerated melting of the glaciers enhanced the total basin runoff, which were the dominant drivers of the dramatic expansion of lakes in the center and northeast of the TP. The increasing precipitation directly expanded the lakes in the center and northeast of the TP. In addition, the increasing temperature accelerated glacial melting, and the glacier–fed lakes exhibited a much faster increasing trend than non–glacier–fed lakes (Huang et al., 2016). In this study, 133 new lakes (1 km^2 < area < 2 km^2) were formed from 1990 to 2015. Similarly, a large number (1099) of new lakes with areas larger than 0.003 km^2 were formed on the TP from 1990 to 2010 (Zhang et al., 2015b). The glacial meltwater charging into the lakes in the form of runoff was an important factor in the expansion of lakes, especially at ≥33°N north of the TP (Song et al., 2014d).

4. Limitations of current study

Generally, the majority of the studies have simulated the hydrology of lakes (Wu et al., 2014; Zhang et al., 2011a) and either ignored the glaciers and permafrost (Lei et al., 2013) or overlooked the groundwater flowing into lakes (Zhou et al., 2013). For instance, some research has only modeled the mass balance of runoff and glaciers within a small watershed (Gao et al., 2012a), or just predicted single glacier variations (Shi et al., 2016). To accurately estimate the contributions of different factors on lakes, many parameters of water balance are required (Zhu et al., 2010b), including precipitation, evaporation, runoff, and other sub basins, ground water, exact ice mass loss of glaciers. Because the in situ meteorological observations for every lake and glacier were insufficient, however, it is difficult to estimate climate change. Thus, diverse national and international cooperation is required for developing "lake–atmosphere–glacier" interaction research on the TP.

Moreover, extensive alpine permafrost underlies the TP (Cheng and Liu, 2008). The in situ monitoring demonstrated that the permafrost is becoming thinner and less contiguous due to global warming, and the groundwater from the shrinkage of permafrost could facilitate the expansion of lakes (Liao et al., 2013). This requires further research. Additionally, extracting the surface area of lakes might inevitably induce more or less misestimating. Errors might also occur when simplifying statistical geometry of the lake pixels to obtain the area of lakes as different sensors possess different image resolutions, such as ~1 km or ~30 m pixel sizes for MODIS and LANDSAT images, respectively. In addition, the periods of images should be chosen within a constant season window for the area of lakes in order to get the largest extent or maintain relatively stable data.

5. Conclusions and implications

We concluded that the mass balance of glaciers on the TP showed that glaciers are experiencing a rapid retreat process, and the dominant reason for the shrinkage of the glaciers was the increasing temperature. In contrast, a positive mass balance of glaciers around the Karakoram Mountains was observed, where the glaciers exhibited a stable or slowly increasing trend due to the relatively stable temperatures and significantly increased precipitation induced by the strengthening of the westerlies.

Both the area and number of lakes have expanded coherently and significantly on the TP from 1990 to 2015. Spatially, the increasing precipitation and accelerating glacier melting enhanced the total basin runoff, which together formed the dominant drivers for the dramatic expansion of lakes in the center and northeast of the TP. Relatively low precipitation, increased temperature, and geographical and geomorphologic limits (lack of inflowing rivers within basin) led to the shrunken or relatively unchanged lakes along the Himalayan Mountains. Uncertain variations in precipitation, strong evaporation and human activities accounted for the fluctuating changes in lakes in the Qaidam Basin. Therefore, different climate factors varied in hydrobalance mechanisms and generated dynamic patterns of lakes on the TP.

This review enhances our scientific understanding of the responses of water resources and the aquatic ecosystems to climate change. The mountain ranges on the TP function as water towers for the Pacific and Indian Ocean water systems, which have profound impacts on water and ecological security. Under the present climate conditions, it is expected that the lakes on the TP will continually expand for a certain period until they reach a "tipping point," when the meltwater of declining glaciers cannot offset the demand for water resources. In this context, severe consequences of limited water resources and many unexpected climate effects, which would seriously threaten the human livelihoods and wellbeing in the South and East Asia, might occur. Therefore, future research should devote more attention to the linkages of lakes and glaciers on the TP, which is critical for developing scientific strategies to control or reduce the potential threats.

Acknowledgments

This research was funded by the National Key Research and Development Program of China (Grant No. 2016YFC0502102, 2016YFC0502002, 2016YFC0501803 and 2016YFC0501802), and the National Science Foundation of China (Grant No. 41671016 and 41501057), West Light Foundation of the Chinese Academy of Sciences, and Youth Innovation Research Team Project (LENOM2016Q0003), the National Natural Science Foundation of China (No. 91647110).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2018.06.012.

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